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A new model for simulating supplemental irrigation and the hydro-economic potential of a rainwater harvesting system in humid subtropical climates

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Abstract:

Here we have developed a new model to simulate supplemental irrigation and the hydro-economic potential of a rainwater harvesting system in rainfed agricultural areas. Using the model, soil moisture in rainfed crop land, supplemental irrigation requirements, rainwater storage in an on-farm reservoir (OFR) system, and surface and ground water availability were predicted. In an irrigated system, an OFR was used to harvest rainwater during the rainy season, and stored water was applied to cropland as supplemental irrigation (SI). An economic analysis was performed to calculate the benefits due to an OFR irrigation system, and gains from increased crop yield and downstream water availability in the irrigated OFR system were compared with rainfed system (i.e. no OFR). In addition, we calculated the impacts of dry and wet seasons on total value gains (grain and water gains) for irrigated and rainfed conditions and performed a sensitivity analysis to quantify the impacts of model input parameters on total value gains. Analyses showed that the OFR system can produce crop yields three times greater than rainfed agriculture. During a water stress season, the total water use in the irrigated system was 65% greater than for the rainfed system. Water use efficiency of the irrigated system was 82% higher than for the rainfed system. In a dry season, the total value gains due to increased crop yield by supplemental irrigation and downstream water availability of the irrigated system were 74% greater than for the rainfed system, while in a wet season the total value gain of the irrigated system was 14% greater than for the rainfed system. A precipitation scenario analysis of wet and dry seasons indicated that the benefits of a rainwater harvesting system can be considerably greater in dry seasons than wet seasons.

Keywords: rainwater harvesting; supplemental irrigation, downstream water availability

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Nomenclature

OFR	*On-farm reservoir*	K_r	*deep absorption constant for deep percolation*
A_{CA}	*catchment area*	*R*	*proportional constant for deep percolation*
A_{CL}	*cultivated area*	D_{wt}	*depth from OFR bottom to the water table*
A_{UC}	*uncultivated area*	K_s	*saturated hydraulic conductivity*
A_{OFR}	*OFR area*	K_c	*crop coefficient*
ds/dt	*change in soil moisture*	Y_c	*calculated crop yield*
dw/dt	*change in OFR water*	Y_{max}	*maximum crop yield*
P_{eff}	*effective precipitation*	Y_{irr}	*actual crop yield under irrigated conditions*
Q_{UC}	*runoff from uncult. land*	Y_{rain}	*actual crop yield under rainfed conditions*
ET_0	*reference evapotrans.*	K_y	*yield response factor*
ET_c	*estimated evapotrans.*	S_m	*available soil moisture*
P	*precipitation*	*TWU*	*total water use*
E_s	*actual soil evaporation*	*WUE*	*overall water use efficiency*
E	*evaporation OFR*	*IWSE*	*irrigation water supply efficiency*
D	*deep percolation*	G_W	*green water*
S	*seepage from OFR*	B_w	*blue water*
SI	*supplemental irrigation*	WV_{OFR}	*water storage in OFR*
SI_{max}	*max. suppl. irrigation*	Q_{spill}	*spill from OFR*
RAM	*readily available soil moisture*	*NRAM*	*non-readily available soil moisture*
Q_C	*runoff from cult. land*	S_{mfc}	*available soil moisture at field capacity*

1. Introduction

The Human Development Report (2010) by the United Nations has emphasized the global water crisis. While predicting a future scenario of water availability under climate change and population growth, Rockström et al. (2009) estimated that by 2050, approximately 59% of the world population will live in areas with limited water available in streams and aquifers. A recent study by Wada et al. (2011) reported that 1.7 billion people suffer from moderate to severe water stress. By 2050, an additional 5,600 km^3/yr of consumptive water use will be needed to meet future food demands (Falkenmark and Rockström, 2006; Falkenmark, 2006). Previous studies suggest that there is considerable potential to improve grain production in rainfed agricultural areas by protecting crops from dry spell damage (Rockström and Rouw, 1997; Rockström, 2003; Wani et al., 2008; Garg et al., 2012; Sahrawat et al., 2010).

On a global scale, agriculture consumes approximately 75% of the world's total water consumption (Falkenmark and Rockström, 2004). Increased water demand from domestic and industrial uses is likely to reduce the amount of water that would be available for agriculture in the future (van der Zaag and Gupta, 2008). This may impact many countries in Asia and sub-Saharan Africa, where agriculture contributes significantly to the gross domestic product (GDP). In India, 17% of the GDP comes from agriculture (U.S. CIA, 2013a) (U.S. Department of States, 2010); and in sub-Saharan Africa, for instance Ethiopia, 47% of the GDP comes from agriculture (U.S. CIA, 2013b). Approximately 94% of the agricultural land in sub-Saharan Africa, and 66% of agricultural land in Asia is rainfed (McCartney and Smakhtin, 2010). Rainfed agriculture dominates the global food supply, for instance, approximately 80% of global cropland is rainfed, which produces 60-70% of the world's food supply (Falkenmark and Rockström, 2004). Hence, agricultural water demand cannot be ignored.

In Asia and sub-Saharan Africa, increasing water resources and improving irrigation management can help improve the productivity of rainfed agriculture (Keller et al., 2000; McCartney and Smakhtin, 2010). Increasing water storage has a vital role in improving global food security, alleviating poverty, and building resilience for adaptation to climate change (IWMI, 2009). While outlining the plan of action to meet future water demands, the World Bank's water resources strategy emphasized investments for increasing water storage (World Bank, 2010).

Large water dams are one option for increasing water storage which have many benefits (Hanjra et al. 2009); however, they negatively impact the environment. Moreover, increasing per capita water storage using large reservoirs may not necessarily increase per capita income in many developing countries (McCartney and Smakhtin, 2010). Additionally, large dams have led to adversely affecting the poor in particular, and have altered river and stream flow in ways that led to degraded riparian ecosystems and natural resources. The result is that the livelihoods of millions of people have been adversely impacted forever (IWMI, 2009).

Negative social, economic, and environmental consequences of large reservoirs have increased an interest in meeting future food needs by rainfed agriculture. A joint report by the Food and Agriculture Organization (FAO) and International Institute of Applied Systems Analysis (IIASA) has estimated that approximately 3 billion hectares of land are suitable for rainfed agriculture (FAO/IIASA, 2000). Another study by Droogers et al. (2001) estimated that approximately 7 billion hectares of land have significant potential for rainfed agricultural production.

A study by Rockström et al. (2003) estimated that a water storage capacity of around 200 mm annually can increase crop yields in many semiarid and dry subhumid savannah regions. Crops are able to avail approximately 100 mm of water from the moisture available in soil profile but need an additional 100 mm of water (1 ha requires 1000 m^3) to achieve maximum crop yield potential (van der Zaag and Gupta, 2008). This water must come from precipitation or supplemental irrigation (*SI*) and when not available, crop yields decrease.

Many studies have reported that the *SI* required to increase rainfed crop yield can be met by harvesting rainwater in small reservoirs (van der Zaag and Gupta, 2008; Pandey et al., 2011; Fox and Rockström, 2003; Rockström et al., 2009). A study by Fox and Rockström (2003) reported a 56% increase in crop yield by applying *SI* to a rainfed crop. Previously, Gunnell and Krishnamurthy (2003), Mialhe et al. (2008), Pandey et al. (2003), Pandey et al. (2006), and Panigrahi et al. (2001) have shown that small ponds, which harvest water during rainy seasons, are useful for providing *SI* to crops. A study by Wisser et al. (2010) estimated the importance of small reservoirs for crop production at a global scale and found that small reservoirs can significantly increase food production in areas where crop yield is severely restricted by the low water availability. In a rainwater harvesting study, Pandey et al. (2006) reported on the application of small sized reservoirs in cropped land for *SI* as well as for fish culturing. Irrigating cropland with water stored in small reservoirs during rainy seasons has been found useful for increasing crop yields in many rainfed regions (Palanisami and Meinzen-Dick, 2001). Despite many published studies on rainwater harvesting in small ponds for *SI*, the tools which can predict the impacts of small reservoirs on crop yield, *SI* requirements, water availability for the *SI*, and total value gains are not available. Quantifying water storage in an OFR and its impacts on the *SI*, water availability downstream, and total value gains are required to calculate the potential benefits of rainwater harvesting system in rainfed agriculture. The objectives of this study therefore are: 1) calculate the soil moisture availability in irrigated and rainfed systems; 2) estimate the supplemental irrigation requirement of a crop; 3) estimate the crop yields in irrigated and rainfed systems; 3) calculate the potential benefits from improved grain production and water availability; 4) estimate the changes in potential benefits under dry and wet conditions; and 5) calculate the impacts of OFR size on the benefits of the irrigated system when compared to the rainfed system.

2. Model development

The model has two major components: 1) prediction of water storage in the OFR and 2) prediction of soil moisture in the cropland area. Figure 1 shows the parameters of the model. For the first component, the change in the OFR water storage was estimated as

$$\frac{dW}{dt} = P + Q_{UL} - E - S - SI - \mathrm{Q}_{spill} \qquad (1)$$

where *dw/dt* is the change in the OFR water storage (mm/day); *P* is the precipitation on the OFR surface (mm); Q_{UL} is the surface runoff from uncultivated land (mm/day); *E* is the evaporation (mm/day) from the OFR; S is the seepage loss from the OFR (mm/day); Q_{spill} is the overflow from the OFR, when water storage (WV_{OFR}) exceeds the OFR water storage capacity (WV_{MAX}); and SI is the supplemental irrigation to the cropland (mm/day).

For the second component, the change in soil moisture in the cultivated land was calculated as

$$\frac{dS}{dt} = P_{eff} - Q_{CL} - ET_c - D + SI + Q_{spill} \tag{2}$$

where ds/dt is the change in soil water (mm/day); P_{eff} is the effective precipitation on the crop land (daily rainfall minus interception losses). During precipitation, a portion of rain is intercepted by canopy cover and the residue layer, which can affect the water balance (Kozak et al., 2007). Previous studies, for instance, Lull (1964) reported an interception loss of 7 – 36% of seasonal rainfall for four different crop canopies (wheat, corn, soybean, and oat). Savabi and Stott (1994) reported an interception loss of 29 to 23% of rainfall. A study by van and Bruijnzeel (2001) used a canopy interception model, and predicted interception loss of an 8 – 19% of total rainfall (1642 mm) over the growing period. Here we used interception losses of 15% of precipitation during cropping periods to include the impacts of canopy cover in the water balance simulation.

In equation 2, ET_c is the calculated evapotranspiration (mm/day); Q_{CL} is runoff from cultivated land; and D is the deep percolation from the crop land (mm/day). In equations 1 and 2, runoff (Q_{UL} and Q_{CL}) was estimated using the SCS curve number equation (USDA-SCS, 1972). The value of S in equation 1 was estimated by multiplying the hydraulic gradient with the saturated hydraulic conductivity (saturated hydraulic conductivity = 1.9 cm/hr) (Massmann et al., 2003). The value of E was estimated using the Penman Method (1948, 1963). Procedures for calculating E and S are described elsewhere (Pandey et al. 2011). The value of ET_c was estimated from the reference evapotranspiration (ET_0) and daily crop coefficient (K_c) using the FAO method (Allen et al., 1998; Doorenbos and Pruitt, 1977). To estimate ET_c, we used a daily crop coefficient for a dry bean crop, which was estimated by interpolating the crop coefficients of four growth stages: initial (25 days); crop development (25 days); mid-season (30 days); and late seasons (20 days). For estimating D of equation 2, we used an approach proposed by Temesgen et al. (2007).

$$D = K_r \max\left(S_m - (1-r)S_{mfc}\right), 0) \qquad (if\ S_m \le S_{mfc}) \tag{3}$$

$$D = S_m - S_{mfc} \qquad (if\ S_m > S_{mfc}) \tag{4}$$

Where D is the deep percolation, and K_r is a parameter, which takes into consideration of the share of deep absorption from storage in the root zone (Temesgen et al., 2007). The quantity r is a constant for defining the soil moisture level, when calculated soil evaporation is less than the optimum soil evaporation (Temesgen et al., 2007). The S_m is the available soil moisture, and S_{mfc} is the soil moisture at field capacity (120 mm).

To incorporate supplemental irrigation into the water balance, we developed an equation for estimating supplemental irrigation (*SI*).

$$SI = \min\left(SI_{max} \cdot A_{cL} \cdot 10^{-3}, WV_{OFR}\right) \tag{5}$$

where *SI* is applied supplemental irrigation to a rainfed crop, and SI_{max} is the maximum allowed supplemental irrigation to the crop. SI_{max} was set as one third of the *RAM*, where *RAM* is readily available soil moisture of 48 mm. A_{CL} is the cultivated crop land area (m^2); and WV_{OFR} is the water storage volume in the OFR (m^3). If WV_{OFR} (water storage in the OFR) was greater than SI_{max}, then *SI* applied to A_{CL} was SI_{max}; however, when WV_{OFR} was less than SI_{max}, *SI* applied was equal to WV_{OFR}. The need for *SI* was determined by readily available soil moisture content. For example, *SI* was applied to A_{CL} when *RAM* was reduced to 50% of the maximum *RAM* (= 48 mm). Here the maximum *RAM* is the difference between available moisture (*AM*) at field capacity (= 120 mm) and non-readily available moisture (*NRAM*) (= 72 mm). Considering *SI* was applied using a sprinkler irrigation system, the irrigation efficiency was set at 75%. 50% of the water loss in irrigation was considered to be evaporation. A previous report (Irmak et al., 2011) proposed typical application efficiencies for sprinkler irrigation from 65 to 90%. Losses due to evaporation in sprinkler systems are reported to be between 30 – 50% (Molle et al., 2012). To understand how changes in irrigation efficiency can potentially impact the benefits of an irrigation system, we performed a sensitivity analysis, which is described in section 3.

In the OFR system, downstream surface water included runoff from A_{CL} and Q_{spill}, whereas under rainfed conditions, it was the sum of runoff from uncultivated land (A_{UL})

and $A_{CL.}$ Downstream groundwater was the sum of deep percolation from uncultivated land and cultivated land, and seepage from the OFR, whereas under rainfed conditions, it was the sum of deep percolation from uncultivated and cultivated land. The green water was estimated as precipitation minus surface runoff, ET_c, and deep percolation. The availability of both blue water (B_w) (downstream surface water and groundwater) and green water (G_w) (soil moisture) was compared in rainfed and irrigated or OFR systems.

To evaluate the benefits of the OFR system in grain production, irrigation water supply efficiency (IWSE) (Irmak et al., 2011) and overall crop water use efficiency (WUE) (Rockström et al., 2003; Rockström et al., 2002) were estimated. The *WUE* is the crop yield divided by the total seasonal water use of the crop (rainfall + supplemental irrigation) (Irmak et al., 2011).

$$IWSE = \frac{(Y_{irr} - Y_{rain})}{SI} \tag{6}$$

$$WUE = \frac{Y_c}{SI + G_w} \tag{7}$$

Y_{irr} and Y_{rain} are the estimated crop yields under irrigated and rainfed conditions, respectively. G_w is green water use, SI is applied supplemental irrigation, and Y_c is the calculated crop yield (kg/ha).

Y_c was estimated using equation 8.

$$Y_c = Y_{max}\left(1 - K_y\left(1 - \left(\frac{ET_c}{ET_{max}}\right)\right)\right) \quad (8)$$

where Y_{max} is the maximum crop yield (6000 kg/ha), ET_c and ET_{max} are the calculated and maximum crop yields, and K_y (1.25) is the yield response factor representing the effect of a reduction in evapotranspiration on yield losses (Smith, 2012),

3. Study area, model inputs, model application, and sensitivity analysis

The model was implemented on a study area of Kharagpur (22° 19′ 48.86″ N, 87° 19′ 25.15″ E; elevation 29 m) (Figure 2), located in the Indo-Gangetic Plain of India. The Indo-Gangetic Plain of India, covering about 44 million ha in West Bengal, Bihar, Uttar Pradesh, Delhi, Haryana, and Punjab, stretching from 21°31' to 32°20' N and 73°16' to 89°52' E is the most important food producing region in South Asia (Ali et al., 2000). The eastern region of the Indo-Gangetic Plain (i.e., West Bengal, Bihar, and eastern Uttar Pradesh) has a humid climate with an annual precipitation of 1000 – 2000 mm. This region is where more than 80% of the total peas and beans are produced in India (Ali et al., 2000). The western region (i.e., Delhi, western Uttar Pradesh, Punjab, and Haryana) has a semi-arid climate with annual precipitation of 500 – 800 mm. In the western region, rice-wheat, sorghum-wheat, cotton-wheat, pearl millet-rape and mustard, etc. are the major cropping systems. In the eastern region, rice-mustard/potato-black gram/mung bean, rice-lentil/chickpea, maize-wheat, sugarcane-wheat, and pigeonpea-wheat are the common cropping systems.

The West Bengal region of the Indo-Gangetic Plain, receives an average annual rainfall of 1527 mm. The soils are fine loamy to clay, deep, and either poorly or moderately drained. Soils pH is slightly acidic to neutral (pH 4.7 – 7.0) (Ali et al., 2000). The mean minimum and maximum air temperatures are 12 ^{0}C and 40 ^{0}C. About 75% of the total annual rainfall occurs during the monsoon season (June – September) (Figure 2A). Average daily precipitation and evapotranspiration are shown in Figure 2B. The study by Droogers et al. (2001) identified this area as having high potential for rainfed agriculture (Figure 2C).

Climate data (precipitation, temperature, relative humidity, wind speed, global solar radiation) were obtained from the Department of Physics and Meteorology, Indian Institute of Technology, Kharagpur, and India Meteorological Department, Govt. of India. The average daily data on precipitation, temperature, relative humidity, and wind speed were estimated from three years (1997, 1998, and 1999) of daily climate data. Daily solar radiation was estimated from 23 years of data set reported in the Solar Radiation Handbook (2008). Pandey et al. (2011) reported additional details on the climate data used for this study.

While simulating soil moisture, supplemental irrigation requirements, runoff, deep percolation, OFR overflow (i.e., spill), evapotranspiration, and water storage in the OFR, we divided a year into two cropping periods: 1) the first cropping season began on Julian days 20-119; and the second ran from Julian days 165 to 264 (Figure 2B). Water storage in the OFR was estimated using equation 1, and the available soil moisture in cultivated land was estimated using equation 2. To calculate deep percolation we used equations 3 & 4. Supplemental irrigation applied to cultivated land was simulated using equation 5. Irrigation and water use efficiencies were estimated using equations 6 & 7. Actual crop yield was calculated using equation 8.

The input parameter values used in the model are shown in Table 1. Required land and OFR related data include: uncultivated land area (A_{UL}; m^2), OFR area (A_{OFR}; m^2), and cultivated area (A_{CL}; m^2). We used A_{UL} of 3 ha; and A_{CL} of 1 ha. The OFR area was set at 13% of the catchment area. A curve number (*CN*) of 82 was used to estimate runoff. The depth of the reservoir was set at 2.5 m. Ground water depth (D_{wt}) and saturated hydraulic conductivity (K_s) were used to estimate seepage (described in Pandey et al., 2011) from the OFR and were set at 6 m and 0.33 cm/hr, respectively. The initial OFR water volume was set at 35% of the OFR water storage capacity. While estimating available soil moisture in cultivated land (method described in section 2), we used the RAM of 48 mm, and the NRAM of 72 mm. Field capacity (*RAM* + *NRAM*) was set at 120 mm. The initial *RAM* value was set to 25% of the *RAM* value. The supplemental irrigation was triggered, when available soil moisture reached 25% of *RAM*. The maximum applied supplemental irrigation was set to one third of *RAM*. An irrigation efficiency of 75% was used in the model considering that *SI* was applied using a sprinkler irrigation system. We considered 50% of the water loss in irrigation as evaporation. Molle et al. (2012) reported 30 – 50% of water losses in irrigation as evaporation. Deep absorption (K_r) and soil evaporation (r) parameters control deep percolation (equations 3 & 4). We set K_r and r of 0.03 and 0.0018, respectively. To determine gains from grains and downstream water availability, we assumed a grain value of 0.25 $ US/kg, surface water value of 0.03 $ US/m^3, and ground water value was set to 25% of the surface water values (Table 1). Using the crop yield, crop values, downstream water availability, and water values, we estimated the total gains.

A sensitivity analysis was performed to understand the impacts of the parameters on total gains. The sensitivities of K_s (saturated hydraulic conductivity), r (parameter influencing deep percolation), initial OFR water volume, CN, and irrigation efficiency to total gains were estimated. By changing the parameter values (shown in Table 1) ± 30%, we calculated the changes in total value gains (total gain in irrigated conditions / total gain in rainfed conditions). In the sensitivity calculation, we changed the value of one parameter at a time, while maintaining the base values (shown in Table 1) of others, and calculated the changes in benefits. A similar approach has been employed previously (Jesiek and Wolfe, 2005). In addition to understanding the impact of parameters on the total gain, we also estimated how OFR sizes (percentages of catchment area) impacted the crop yield.

Further, we calculated the impacts of precipitation on the total value gains. We simulated the impacts of normal precipitation (average of three years: (1997, 1998, and 1999)), moderately dry (70% of the normal precipitation), dry (40% of the normal precipitation), moderately wet (130% of the normal precipitation), and wet (160% of the normal precipitation) conditions. The total value gain in irrigated and rainfed conditions were estimated to understand how different precipitation conditions can potentially impact the benefits of irrigated system when compared to rainfed system.

4. Result and Discussion

Figure 3 shows the soil moisture of irrigated and rainfed cropping systems, OFR water, and supplemental irrigation. Figure 3A shows variations in the OFR water volume and soil moisture, while Figure 3B shows the daily precipitation, applied supplemental irrigation, and soil moisture. Soil moisture levels during the cropping season 1 (20 – 119 days) under rainfed conditions (shown as a red dotted line) were considerably lower than the irrigated conditions (shown as a green line). Under irrigated conditions soil moisture of the cropped land was elevated by the supplemental irrigation (Figure 3B). To mitigate the impacts of the dry spells *SI* was triggered (green vertical bar of Figure 3B), which improves the soil moisture. During these dry spells a total of 109 mm of *SI* was applied to cropland (Table 2). If irrigation water is not available during dry spells, the crop yield may decrease (Fox and Rockström, 2003). While studying the impacts of *SI* on Sorghum (*Sorghum Bicolor* (L.)) crop yield, Fox and Rockström (2003) reported varying degrees of dry spells among different seasons which lasted a few days to several weeks. In three seasons, the authors reported 3 – 6 dry spells in each season; and 60 to 90 mm of cumulative *SI* was applied in each season to mitigate the impacts of dry spells on crop yields (Fox and Rockström, 2003). Unlike season 1, precipitation during season 2 improved. In both systems, rainfed and irrigated, soil moisture availability was greater than in season 1. Improved soil water availability (Figure 3A and 3B) in cropland by enhanced precipitation resulted in increased crop yields for both systems without supplemental irrigation.

Table 2 shows comparative water balances, crop yields, and water use efficiencies for both seasons for irrigated and rainfed conditions. The total water use (TWU) in season 1 was 262 mm, and the *SI* contributed approximately 42% of the total water use.

Green water (G_w) contribution was about 58% of the total water use. Under rainfed conditions, however, green water was the main source of water for the crop. In season 1, the total water use of the rainfed system was 159 mm (61% of the irrigated). The WUE of the rainfed system in season 1 was 55% of irrigated conditions (Table 2). In season 2, however, the WUE of the rainfed system increased to 98%, when compared to irrigated system because of improved precipitation. A previous study by Fox and Rockström (2003) reported on the importance of supplemental irrigation in increasing the rainwater use efficiency for Sorghum crops. The authors reported rainfed and irrigated water use efficiencies. The water use efficiencies of irrigated cropland were 30 – 40% greater than the rainfed system, when supplemental irrigation was applied without fertilizers; however, when supplemental irrigation was combined with fertilizers, rainfed water use efficiencies increased to 137 – 166% of the rainfed conditions,

The impact of *SI* on crop yields can vary depending on the seasonal precipitation. For example, the improved precipitation in season 2 compared to season 1 reduced the dependence of crop growth on the *SI* (Table 2 and Figure 3B). The G_w in season 1 was 44% of season 2 (for rainfed conditions). The greater availability of G_w in the rainfed system as well as in the irrigated system in season 2 reduced the impact of *SI* on crop yields. The total applied *SI* in season 2 for irrigated condition was only 14 mm (13% of the *SI* of season 1) (Figure 3B; Table 2). In the irrigated system, the total water use over the two cropping seasons (seasons 1 & 2) was 613 mm, while in the rainfed system it was 517 mm (84% of irrigated). In the irrigated system, the average crop yield of the two seasons was 41% greater than for the rainfed system (Table 2).

Fox and Rockström (2003) studied supplemental irrigation for dry-spell mitigation of rainfed agriculture in the Sahel, and found that the *SI* can be a tool for small-farmers to increase crop yields and to protect crops from complete failure due to dry spells (Rockström and Barron, 2007). The authors reported applying *SI* of 60 – 90 mm, which resulted in significant ($P < 0:001$) increase in grain yield (Sorghum (*Sorghum Bicolor* (L.))). For example, the *SI* application resulted in 1.6 times higher grain yield when compared to rainfed conditions. Further increase in crop yield was observed, when the *SI* application was combined with a fertilizer application.

Others have reported similar results. For example, Rockström and Barron (2007) found that the water productivity gain in rainfed regions can be greatest when supplemental irrigation is combined with nutrient management and improved tillage practices. For instance, a supplemental irrigation study (Rockström et al. (2002) carried out in Burkina Faso (seasonal rainfall of 418 – 667 mm) and Kenya (seasonal rainfall of 196 – 557 mm) reported 37 – 38% increase in crop yields (Sorghum) by supplemental irrigation alone; however, when supplemental irrigation was combined with fertilizer application, the crop yield of irrigated land increased to 70 – 300% when compared to the rainfed system.

Among two seasons, crop yields varied considerably in rainfed as well as in irrigated systems. Table 3 shows gain of an OFR system over the rainfed system. Annual water balance of cultivated land, uncultivated land, and OFR is shown in the Table. The ET_c of cultivated land in irrigated system was 21% greater than rainfed system. Downstream ground water availability (recharged ground water through seepage from the OFR) in the OFR system was increased by 18% in the irrigated system when compared to the rainfed system. One of the major water losses from the OFR was seepage loss, which approximated 41% of the total water loss. Previous studies (Sur et al., 1999; Pacey and Cullis, 1998; and Fox and Rockström, 2003) have also reported seepage as a major water loss in water storage in earthen reservoirs. Fox and Rockström (2003) reported 44 – 89% of total water loss as seepage.

Soil moisture variability in the irrigated system shown in Figure 3 indicates that the necessity of supplemental irrigation to improve soil moisture of cropped land largely depends on precipitation patterns (the absence of dry spells during a cropping season can potentially reduce the demand of *SI* (as shown in season 2)). When natural precipitation conditions improved, the crop yields of rainfed and irrigated condition were identical (Table 2), and the grain value gains were comparable between the two systems. The simulation shows that the highest benefit of the OFR system occurs during a season with frequent dry spells (Figure 3B). Seasonal variation during the monsoon rainfall of India is considerably high (Webster and Hoyos, 2004). The authors reported rainfall variation within 10% of the average (1986 – 2002) during the normal rainfall season, in the wet season rainfall can be greater than 110%, and in the dry season rainfall can be less than 70 - 90% of the average rainfall.

Figure 4 shows the impact of precipitation on total value gains for a normal rainfall season (a season of average daily precipitation of 1997, 1998, and 1999), moderately wet (130% of the normal precipitation), wet (160% of the normal), moderately dry (70% of the normal), and dry conditions (40% of the normal precipitation). Table 4 shows the impacts of rainfall (i.e., precipitation pattern) on crop yields, supplemental irrigation, and total value gains.

The benefits of an OFR system were considerably higher during the dry season (Table 4). For example, the average crop yields (of season 1 & season 2) of irrigated cropland in the dry season was 75% greater than the rainfed system, while in the moderately dry season it was 46% greater than rainfed system. In wet conditions, the difference in crop yields (among irrigated and rainfed) was reduced – in moderately wet conditions, irrigated crop yield was 34% greater than rainfed, and in wet conditions it was 32% of rainfed. In Figure 4, the value gains (downstream water value, grain value, and total value gain (grain and water)) of the irrigated system (% of rainfed) are plotted for five different precipitation scenarios. The total value gains in the irrigated system (% of rainfed) were higher in dry seasons when compared to wet seasons. For example, during normal precipitation, the total value gains in irrigated cropped land were 31% greater than rainfed; while during the dry season the total value gains in irrigated conditions were 74% greater than rainfed system. During wet conditions, however, the total value gains of irrigated cropland were only 14% greater than the rainfed land.

In addition to a precipitation scenario analysis, we also performed calculations to understand how OFR size (percentage of catchment area under OFR) can potentially impact crop yield under normal precipitation conditions. We varied OFR sizes from 1 to 15%, and calculated crop yields, supplemental irrigation, downstream surface and ground water availability, and value gains. The crop yield, supplemental irrigation availability, and value gains of irrigated and rainfed cropland under different OFR sizes are shown in Figure 5A, 5B, and 5C, respectively. Crop yields in irrigated and rainfed system was almost identical in season 2 (Figure 5A) for all OFR sizes. Crop yield in season 2 was approximately 6 times greater than season 1 (in both irrigated and rainfed conditions) potentially due to the improved precipitation. Supplemental irrigation under different OFR sizes (Figure 5B) varied from 21 – 113 mm and 29 – 37 mm for cropping season 1 and 2, respectively. The average *SI* (of two seasons) varied from 26 to 72 mm. Total value gains under the different OFR sizes are shown in Figure 5C. The gains from grain dominated the total value gains in rainfed as well as in irrigated conditions. For example, the gains of water and grain in irrigated conditions varied from 85 – 97 US$ and 1,886 – 2,508 US$, respectively. The gain from grain in rainfed system was 1,709 US$, while gain from water was only 122 US$.

The sensitivity of total value gains to parameter values (i.e., K_s, *r*, initial OFR water volume, *CN*, and irrigation efficiency) were estimated, and results are shown in Figure 6. The parameter values were changed from 70% to 130% of the base parameter values shown in Table 1. The x-axis shows the percentage of each parameter base value while the y-axis shows the corresponding changes in total value gains (percentage of rainfed system). Initial OFR water storage was varied from 29 to 45% of the OFR water storage capacity. The K_s value was changed from 0.28 to 0.43 cm/hr, *CN* values (base value of 82) were changed ± 30% of base value. Irrigation efficiencies were changed from 63 to 97%. At a *CN* of 94, gains from grain in irrigated was 151% of the rainfed, while at a low *CN* value of 70 it was reduced to 123% of rainfed. At high *CN* values (CN of 94), the ground water value gain in irrigated over rainfed was considerably high, potentially due to increased water availability in the OFR and subsequent recharge from the OFR.

Generally, high values of the initial OFR water volume resulted in improved total gains (irrigated over rainfed). When the initial OFR water volume was increased, grain production of irrigated cropland also increased, mainly due to the enhanced supplemental irrigation availability. This indicates that the OFR water storage from previous years (left over from the previous season) can potentially change the total gains of irrigated systems. Similarly, improved irrigation efficiency also increased crop yields, and total gains of irrigated land were increased over rainfed land. The increased K_s values; however, resulted in reduced total gains of irrigated over rainfed systems (Figure 6). At greater K_s values, the seepage from the OFR increased, which reduced the water availability in the OFR for supplemental irrigation.

The model simulation presented here is based on a rainfed region of India. The predictions indicate that the benefits of rainwater harvesting (i.e., crop yield, downstream water availability, supplemental irrigation requirement, and value gains) can vary considerably from one region to another. In order to verify the robustness of the model, the authors suggest implementing the model in different climate and geologic conditions. Many assumptions (described in sections 2 & 3) were needed to simplify the model, which still needs further verification. A simple precipitation analysis and sensitivity analysis described here are helpful in understanding the impacts of wet/dry conditions and parameter assumptions on the benefits of the OFR system; however, use of measured climate data (i.e., rainfall for extended period of time) and soil characteristics would also help improve model predictions and assumptions.

In summary, results showed that rainwater harvesting by OFR and the subsequent use of stored water for irrigation can potentially increase the benefits of rainfed agriculture. The rainwater harvesting in the OFR provided supplemental irrigation, and it also increased the downstream ground water availability. The supplemental irrigation to cropland resulted in increased water use efficiencies and crop yields. The increase in crop yield and downstream ground water enhanced the total value gains of the irrigated system over the rainfed system. A simple precipitation scenario analysis was used to understand the potential impacts of wet and dry seasons on the total value gains and indicated that the benefits of rainwater harvesting can vary seasonally. The benefits can be considerably greater in dry seasons than in wet seasons. For example, the total value gains of the irrigated system during dry seasons (when precipitation was 30% - 60% below average) were 74% greater than the rainfed system. The total value gains of the irrigated system over the rainfed system was less during wet seasons.

5. Conclusions

In this study we developed a new model to simulate the supplemental irrigation, water balance of rainfed crop land, and water storages of the OFR to predict hydro-economic potential of rainwater harvesting system for rainfed agriculture. The model was employed for predicting supplemental irrigation and potential use of rainwater for providing supplemental irrigation to crops in a rainfed area. The benefits of on-farm reservoir systems (OFR) were calculated. Results show that an OFR can be a source of water for providing supplemental irrigation to rainfed crops. The OFR system can increase the crop yield of rainfed agriculture considerably (30 – 40%). It can enhance ground water availability. Using the grain and water values, we estimated the total value gains of irrigated and rainfed croplands. The total value gains for the irrigated system were 31 – 74% greater than the rainfed system. The precipitation patterns (dry and wet seasons) controlled the total value gains. The benefits of the OFR system were considerably greater during the dry season than the wet season.

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Figure captions

Figure 1. Conceptual water flows in the simulation model used for predicting OFR water levels, supplemental irrigation, and benefits from the OFR system. A_{UC} is uncultivated land (catchment area), Q_{UL} is runoff from uncultivated land to OFR, A_{CL} is cultivated land, and Q_{CL} is runoff from cultivated crop land. Q_{spill} is overflow from the OFR, when WV_{OFR} (OFR water storage) is greater than WV_{MAX} (OFR maximum water storage capacity).

Figure 2. Monsoon (June-September) rainfall variations, study area climate, and rainfed agriculture potential. A) monsoon rainfall (data source: India Meteorological Department (2013)); B) climate (precipitation and reference ET_0) of study area (Kharagpur, West Bengal); and C) potentials for rainfed agriculture in India (high, moderate, low, and very low legends indicate the levels of rainfed agriculture potential) (map and data source: Droogers et al., 2001)

Figure 3. Soil moisture variations in irrigated and rainfed conditions, OFR water storage, precipitation, and supplemental irrigation of cropped land. A) Soil moisture for irrigated conditions, soil moisture for rainfed conditions, and water volume in the OFR; and B) precipitation, supplemental irrigation, soils moisture in irrigated condition, and soil moisture in rainfed condition.

Figure 4. The impacts of precipitation scenarios on value gains of the irrigated system. Precipitation scenarios are dry (when daily precipitation was 30% less than the normal precipitation), moderately dry (daily precipitation was 60% less than the normal precipitation), normal precipitation (average precipitation of three years (1999, 2000, and 2001), moderately wet (precipitation was 30% more than the normal precipitation), and wet (precipitation was 60% more than the normal precipitation).

Figure 5. Crop yield, supplemental irrigation availability, and value gains in different OFR sizes. A) Crop yield under different OFR sizes; B) supplemental irrigation availability under different OFR sizes; C) values gains (i.e., gains from water and grain) under different OFR sizes.

Figure 6. Sensitivity of parameter values to the total value gain in the irrigated system (as a percentage of the rainfed system). Parameter values were changed from 70 to 130% (x-axis) of the base values. The impacts of the parameter values on the total gain are shown in the y-axis.

Table 1. Input parameters for simulations

Input parameters	Unit	Value
Catchment area	ha	3
Reservoir area (% of catchment area)	%	13
Uncultivated area	ha	2.7
Cultivated area	ha	1
Interception storage	%	15
Curve number CN		82
Depth of reservoir	m	2.5
Start storage reservoir (% of storage capacity)	%	35
Ground water depth (D_{wt}) base value	m	6
Saturated hydraulic conductivity (K_s) base value	cm/hr	0.33
Readily Available Moisture (RAM)	mm	48
Initial RAM (% of RAM)	%	25
Non-readily accessible moisture (NRAM)	mm	72
Level of moisture for triggering supplemental irrigation (% of RAM)	%	50
Irrigation efficiency	%	75
Fraction irrigation loss through evaporation	%	50
Minimum evaporation (% of ET_0)	%	50
Maximum crop yields (Y_{max})	kg/ha	6000
Parameters for deep absorption from root zone (K_r)		0.05
Parameters for defining soil evaporation (r)		0.0018
Grain value	US$/kg	0.25
Surface water value	US$/m^3	0.03
Ground water value	of surface water	1/4

Table 2. Comparative water balance and water use efficiency in cropping seasons

Duration	P	Q	ET_a	D	SI	Y_c	G_w	TWU	WUE	IWSE
	mm	mm	mm	mm	mm	Kg/ha	mm	mm	Kg/m^3	Kg/m^3
Season 1										
Irrigated	123	3.2	319	0.7	109	4,575	153	262	1.75	2.80
Rainfed	123	3.2	160	0.0	NA	1,526	159	159	0.96	NA
Season 2										
Irrigated	811	97	358	315	14	6,000	337	351	1.71	0.0
Rainfed	811	97	358	294	NA	6,000	358	358	1.68	NA
Total										
Irrigated	933	100	677	316	123	5288*	490	613	1.73*	1.4*
Rainfed	933	100	517	294	NA	3763*	517	517	1.32*	NA

* Average of seasons 1st and 2nd

Table 3. Annual water balance of uncultivated, cultivated land, and OFR; otal value gains of irrigated and rainfed systems.

	Uncultivated land		Cultivated land		OFR
	Irrigated	Rainfed	Irrigated	Rainfed	
Q (m^3/yr)	-3,179	-3,654	-1,218	-1,218	0
ET (m^3)	-16,931	-19,460	-9,463	-7,821	NA
D or S (m^3/yr)	-12,693	-14,590	-12,693	-14,590	-4,786
E (m^3/yr)	NA	NA	NA	NA	-5,655
SI (m^3/yr)	NA	NA	+ 1,224	NA	-1,224

	Irrigated	Rainfed
Downstream surface water (m^3/yr)	1,218	4,872
Downstream ground water (m^3/yr)	21,233	18,119
Downstream blue water (m^3/yr)	22,451	22,991
Downstream surface water value (U.S.$)	37	146
Downstream groundwater value (U.S.$)	159	136
Total blue water value (U.S.$)	196	282
Total grain value (US$)	2,644	1,882
Total (US$)	2,840	2,164

[*] negative and positive sign indicates water out and in, respectively

[**] grain value of 0.25 US$/kg, surface water value of 0.03 US$/$m^3$; and ground water value of 0.25 US$/$m^3$ were used in value estimation.

Table 4: Impacts of precipitation pattern on supplemental irrigation, crop yields, and value gain in irrigated and rainfed conditions.

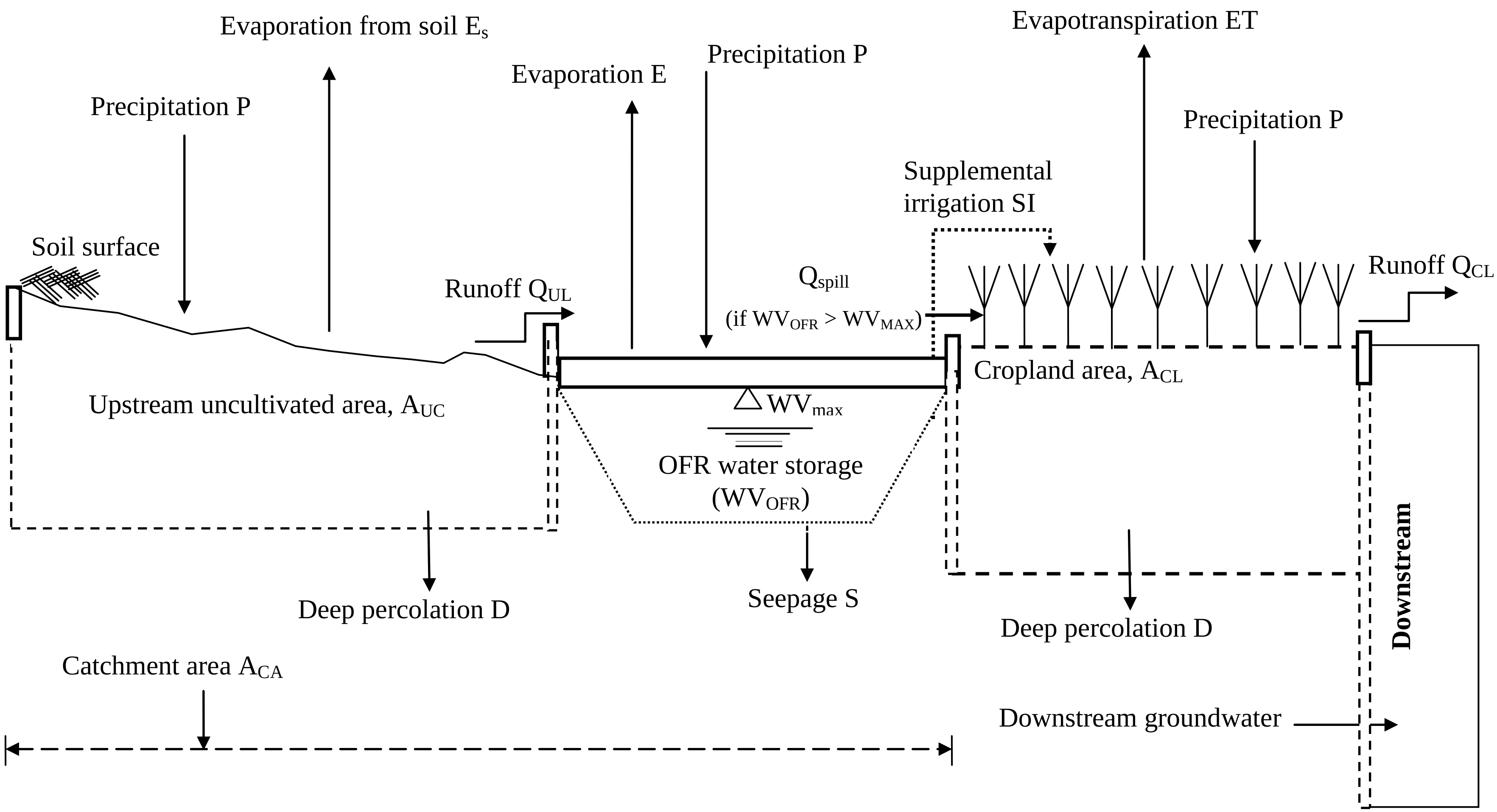
*Supplemental irrigation (total of seasons 1st and 2nd)

**Y_c (average of seasons 1st and 2nd)

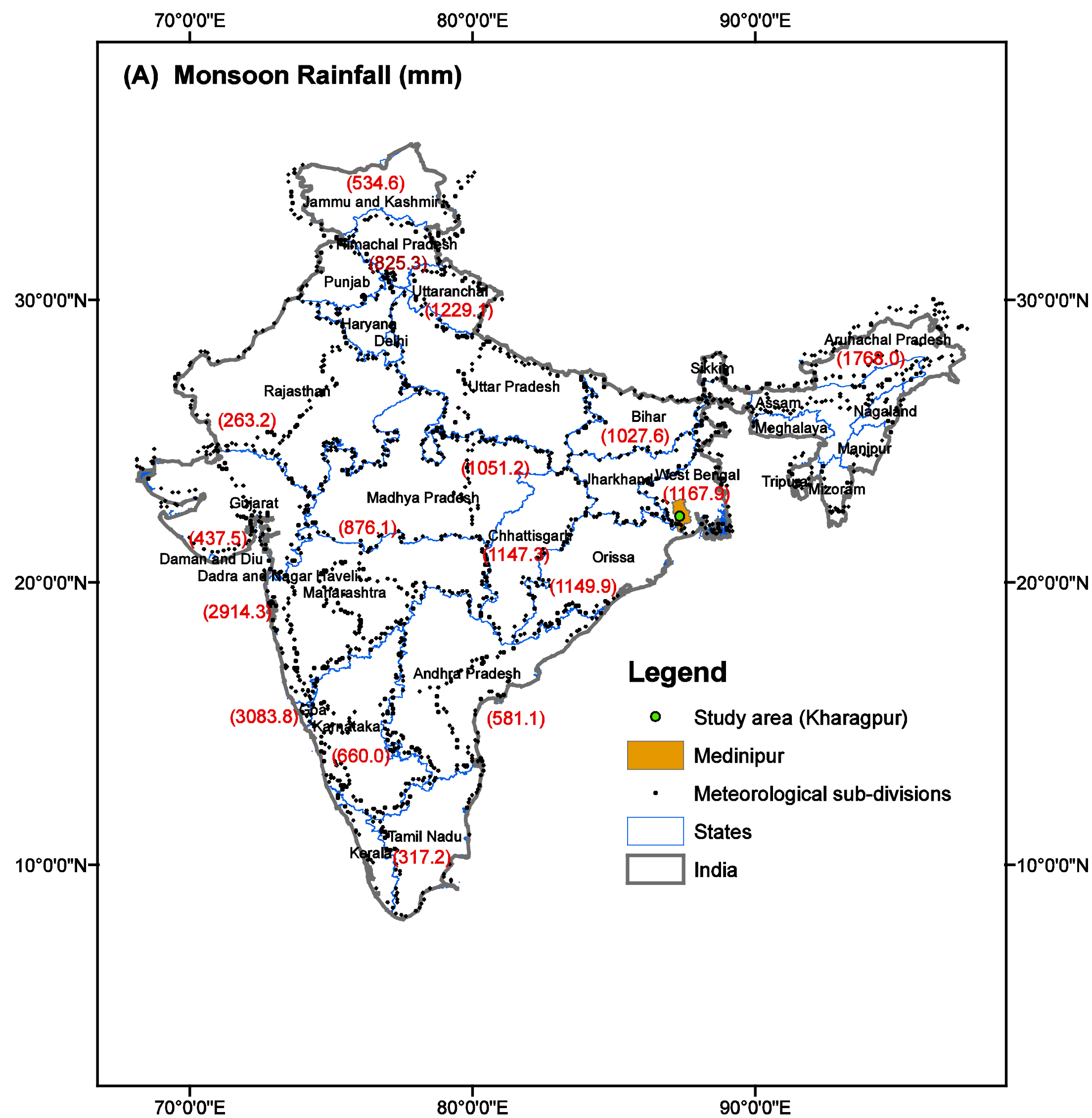
Parameters	Average (i.e., normal) rainfall		Moderate wet (130% of average rainfall)		Wet (160% of average rainfall)		Moderate dry (70% of average rainfall)		Dry (40 % of average rainfall)	
	Irrig.	Rainf.	Irrig.	Rainf.	Irrig.	Rainf.	Irrig.	Rainf.	Irrig.	Rainf.
Crop yield, Y_c (kg/ha)	5287	3763	5429	4039	5704	4300	4995	3419	4265	2438
Supplemental Irrigation (mm)	123	0	112	0	112	0	145	0	128	0
Value of downstream surface water (US $)	37	146	67	268	105	419	15	59	3	12
Value of downstream ground water (US $)	159	136	231	207	296	273	80	63	16	4
Total water value (i.e., blue water) (US $)	196	282	298	475	400	692	95	122	19	16
Total value grain (US $)	2644	1882	2714	2019	2852	2150	2497	1709	2132	1219
Total value (grain + blue water) (US $)	2840	2164	3012	2494	3253	2842	2592	1832	2151	1234

** grain value of 0.25 US$/kg, surface water value of 0.03 US$/m3; and ground water value of 0.25 US$/$m^3$ were used in value estimation.

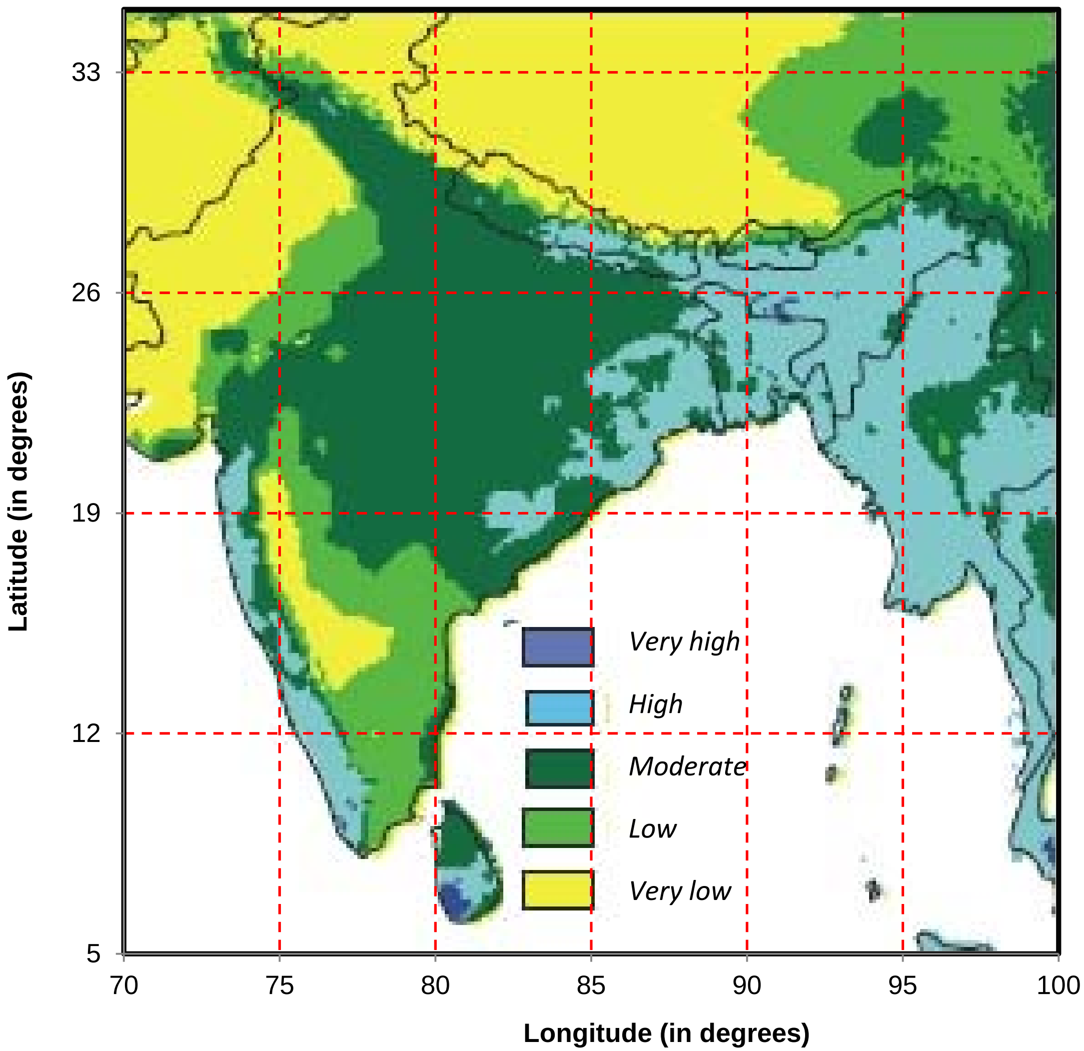
Figure 1.

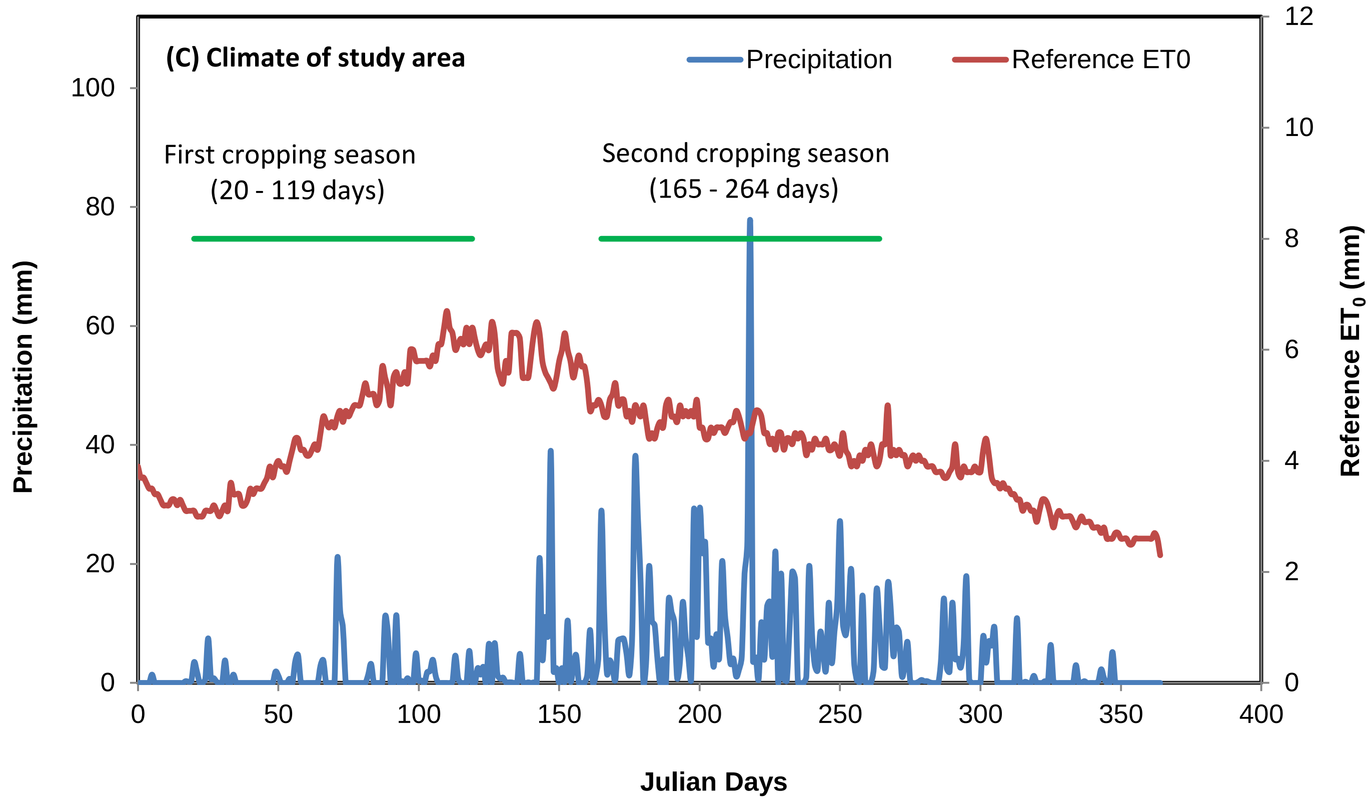

Evaporation from soil E_s
Precipitation P
Evaporation E
Precipitation P
Evapotranspiration ET
Precipitation P
Supplemental
irrigation SI
Soil surface
Runoff Q_{UL}
Q_{spill}
(if WV_{OFR} > WV_{MAX})
Runoff Q_{CL}
Cropland area, A_{CL}
Upstream uncultivated area, A_{UC}
WV_{max}
OFR water storage
(WV_{OFR})
Downstream
Deep percolation D
Seepage S
Deep percolation D
Catchment area A_{CA}
Downstream groundwater

Figures 2.


70°0'0"E
80°0'0"E
90°0'0"E
30°0'0"N
20°0'0"N
10°0'0"N
(A) Monsoon Rainfall (mm)
(534.6)
Jammu and Kashmir
Himachal Pradesh
(825.3)
Punjab
Uttaranchal
(1229.1)
Haryana
Delhi
Rajasthan
(263.2)
Uttar Pradesh
Sikkim
Arunachal Pradesh
(1768.0)
Bihar
(1027.6)
Assam
Meghalaya
Nagaland
Manipur
(1051.2)
Jharkhand
West Bengal
(1167.9)
Tripura
Mizoram
Madhya Pradesh
Gujarat
(876.1)
(437.5)
Chhattisgarh
(1147.3)
Orissa
Daman and Diu
Dadra and Nagar Haveli
Maharashtra
(1149.9)
(2914.3)
Andhra Pradesh
Goa
(3083.8)
Karnataka
(581.1)
(660.0)
Tamil Nadu
Kerala
(317.2)
Legend
Study area (Kharagpur)
Medinipur
Meteorological sub-divisions
States
India

(B) Potential for rain-fed agriculture (Droogers et al. 2001)





(C) Climate of study area
Precipitation
Reference ET0
First cropping season
(20 - 119 days)
Second cropping season
(165 - 264 days)
Precipitation (mm)
Reference ET_0 (mm)
Julian Days
0
20
40
60
80
100
0
2
4
6
8
10
12
0
50
100
150
200
250
300
350
400

Figure 3:

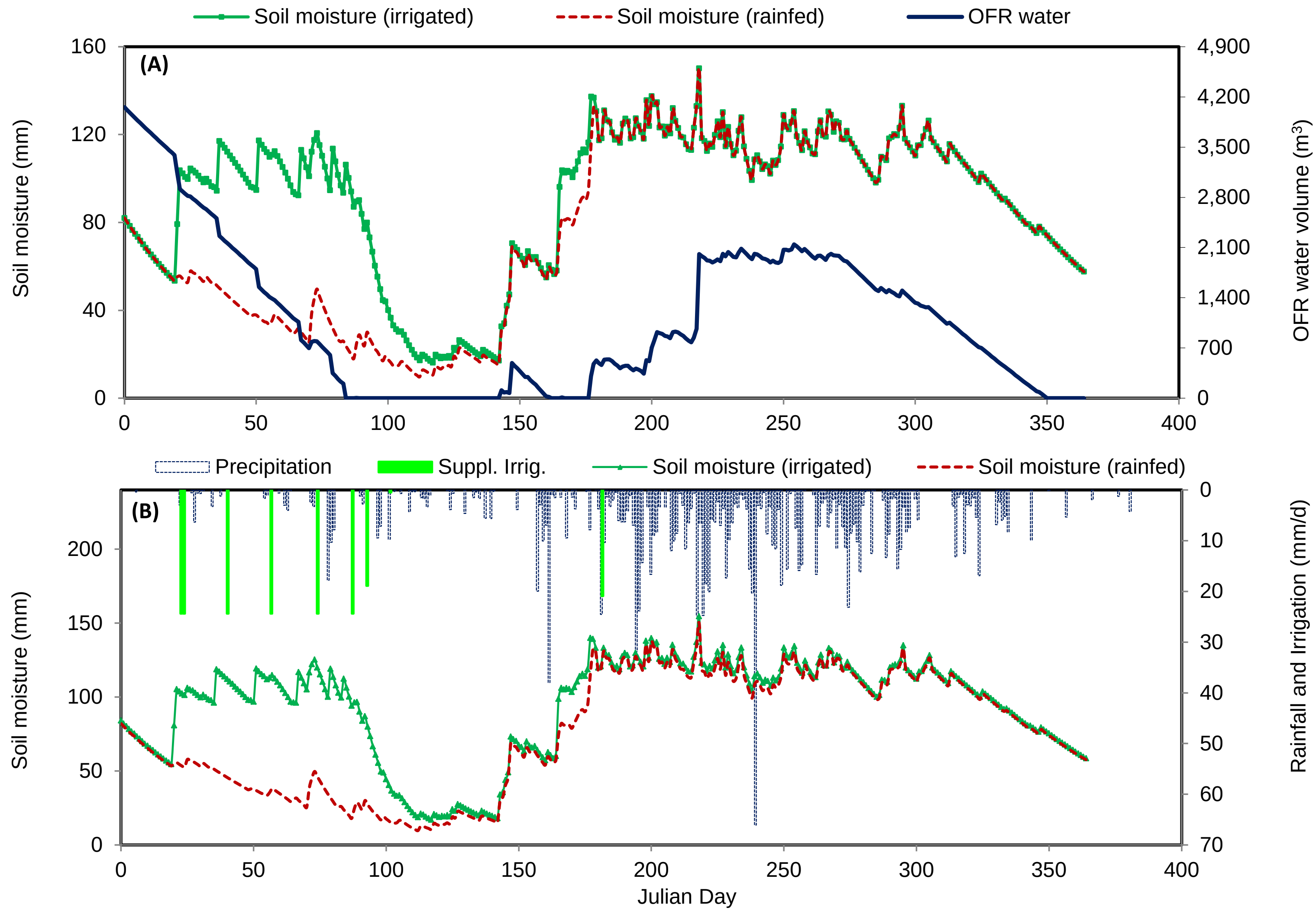
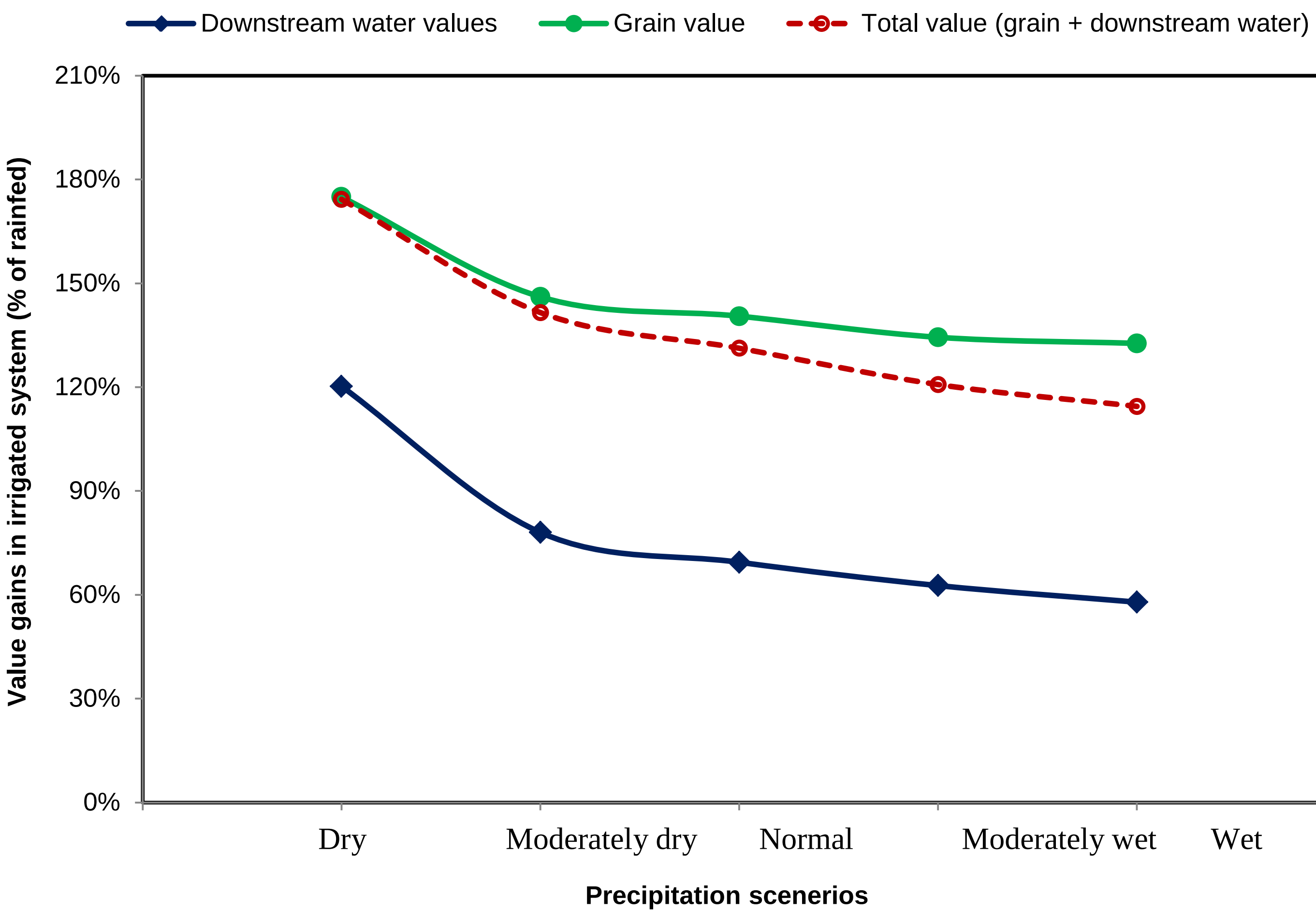
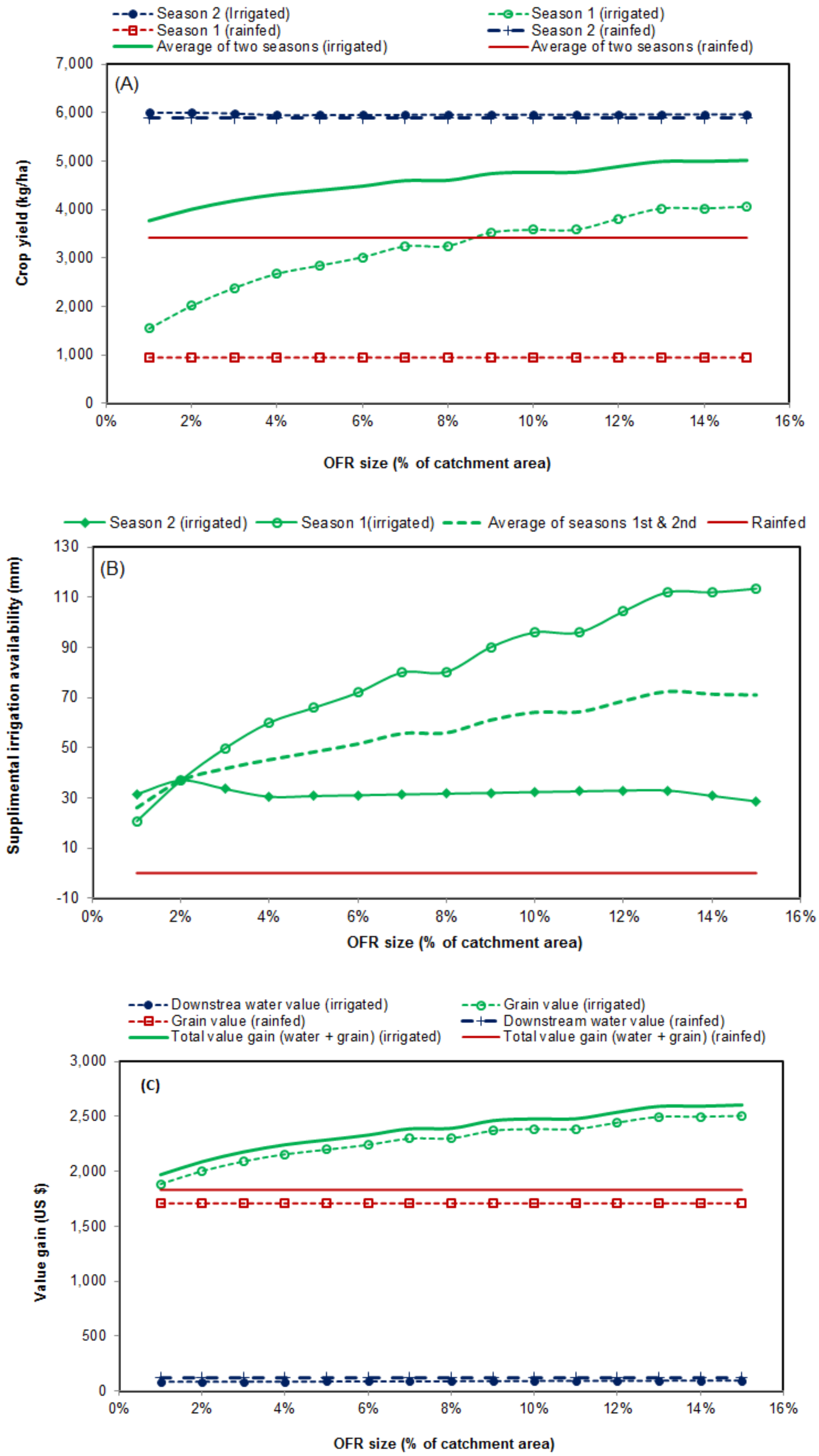

Soil moisture (irrigated)
Soil moisture (rainfed)
OFR water
(A)
Soil moisture (mm)
OFR water volume (m^3)
160
120
80
40
0
4,900
4,200
3,500
2,800
2,100
1,400
700
0
0
50
100
150
200
250
300
350
400
Precipitation
Suppl. Irrig.
Soil moisture (irrigated)
Soil moisture (rainfed)
(B)
Soil moisture (mm)
Rainfall and Irrigation (mm/d)
200
150
100
50
0
0
10
20
30
40
50
60
70
Julian Day

Figure 4



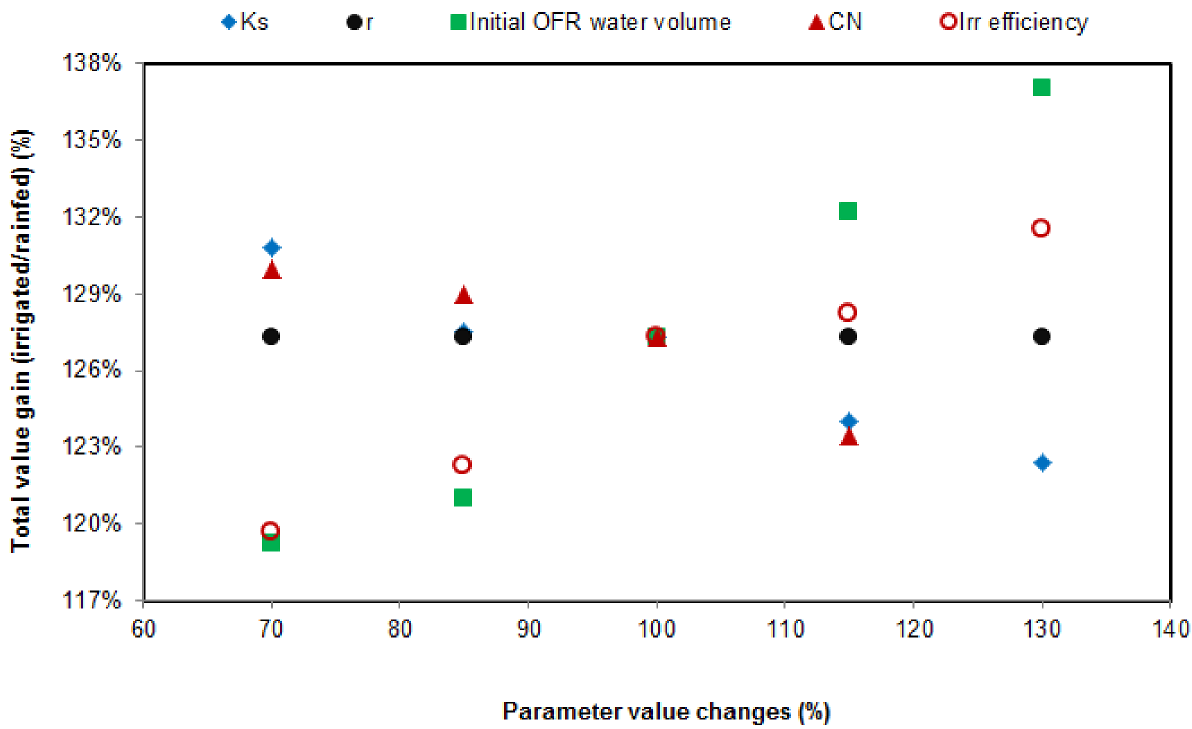
Downstream water values
Grain value
Total value (grain + downstream water)
210%
180%
150%
120%
90%
60%
30%
0%
Value gains in irrigated system (% of rainfed)
Dry
Moderately dry
Normal
Moderately wet
Wet
Precipitation scenerios

Figures 5:



Season 2 (Irrigated)
Season 1 (rainfed)
Average of two seasons (irrigated)
Season 1 (irrigated)
Season 2 (rainfed)
Average of two seasons (rainfed)
(A)
Crop yield (kg/ha)
OFR size (% of catchment area)
Season 2 (irrigated)
Season 1(irrigated)
Average of seasons 1st & 2nd
Rainfed
(B)
Supplimental irrigation availability (mm)
OFR size (% of catchment area)
Downstrea water value (irrigated)
Grain value (rainfed)
Total value gain (water + grain) (irrigated)
Grain value (irrigated)
Downstream water value (rainfed)
Total value gain (water + grain) (rainfed)
(C)
Value gain (US $)
OFR size (% of catchment area)

Figure 6


Ks
r
Initial OFR water volume
CN
Irr efficiency
Total value gain (irrigated/rainfed) (%)
138%
135%
132%
129%
126%
123%
120%
117%
60
70
80
90
100
110
120
130
140
Parameter value changes (%)